

Deep Space Atomic Clock Overview

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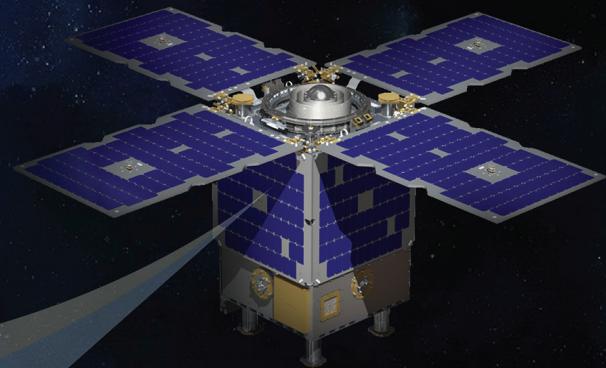
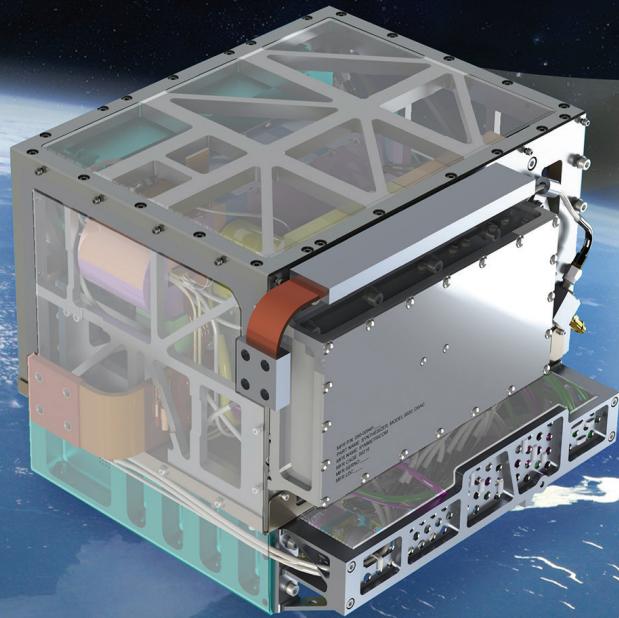


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Deep Space Atomic Clock

A Technology Demonstration Mission



TDM

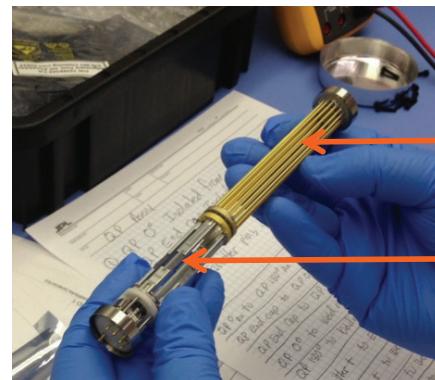
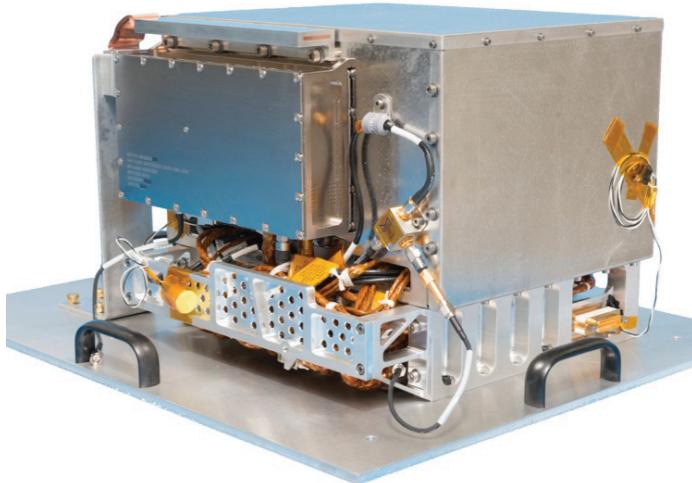


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DSAC Technology Demonstration Mission

DSAC Demonstration Unit



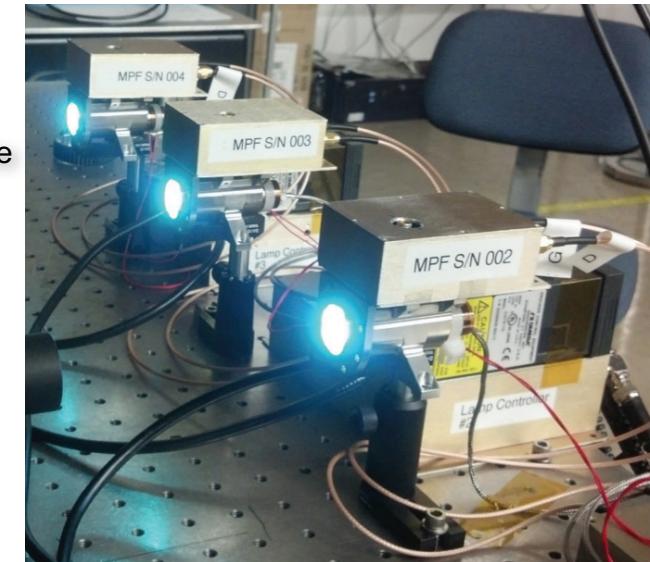
Multi-pole
Trap

Quadrupole
Trap

Titanium Vacuum Tube



Mercury UV Lamp Testing



Develop advanced prototype ('Demo Unit') mercury-ion atomic clock for navigation/science in deep space and Earth

- Perform year-long demonstration in space beginning Sept 2017+ – advancing to TRL 7
- Focus on maturing the new technology – ion trap and optical systems – other system components (i.e. payload controllers, USO, GPS) size, weight, power (SWaP) dependent on resources/schedule
- Identify pathways to 'spin' the design of a future operational unit (TRL 7 → 9) to be smaller, more power efficient – facilitated by a detailed report written for the next DSAC manager/engineers

Broad Benefits for Enhanced Exploration & National Security

Enable routine use of 1-Way tracking - more flexible/robust mission ops than with 2-Way tracking

- *Ex.: 3X more radio science data during Europa flybys without constraining other science*

Fundamental to enabling real-time, on-board deep space radio navigation

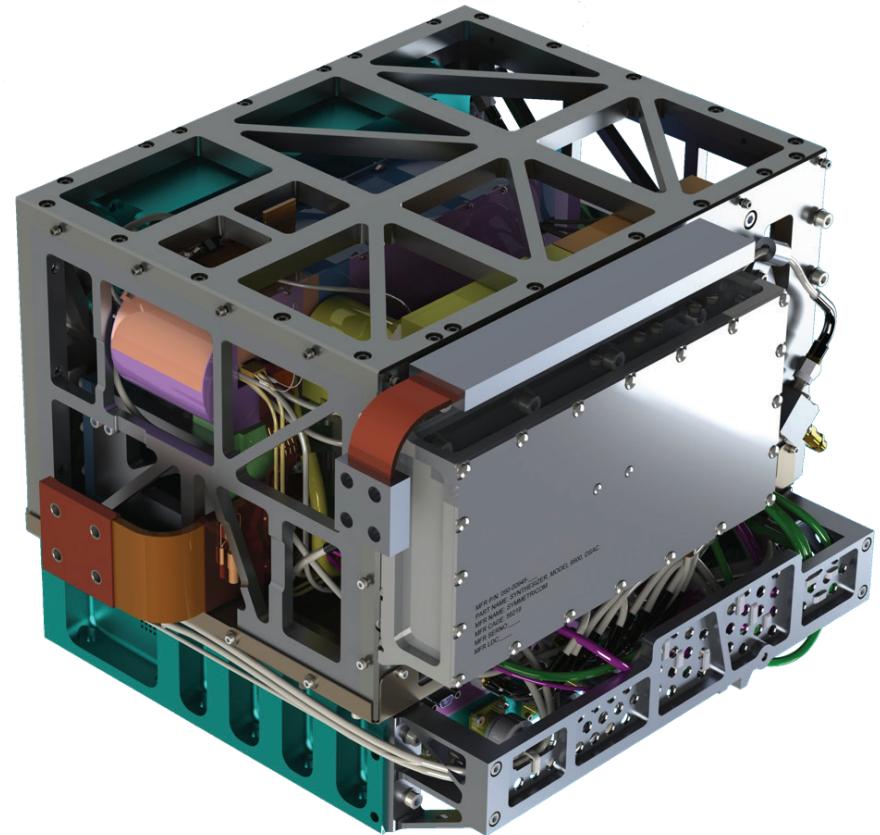
- *Ex.: Trajectory knowledge to 10's of meters at entry to Mars' atmosphere*

Enable use of existing DSN Ka-band downlink tracking capability – improve data accuracy by 10X

- *Ex.: Determine Mars' long period gravity and orientation to GRACE-quality using one spacecraft*

National security resource to GPS, protected command and control, and other applications

- *Ex.: Improves upon existing GPS clock performance by 50 times or more*



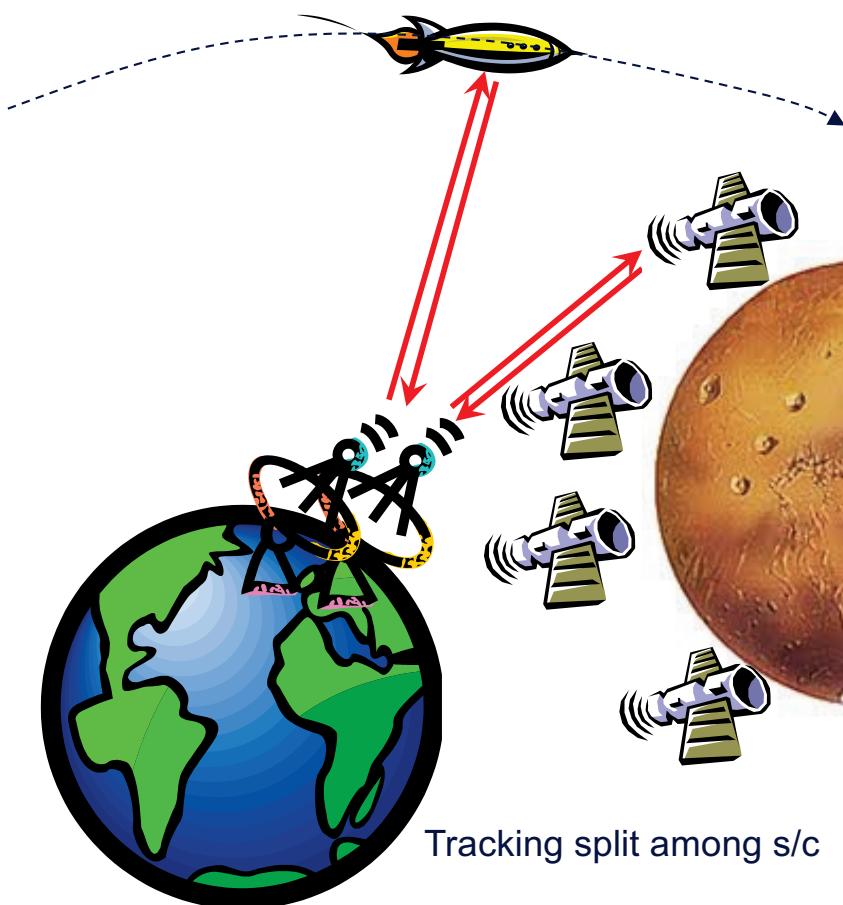
DSAC Benefits the DSN and Mission Operations



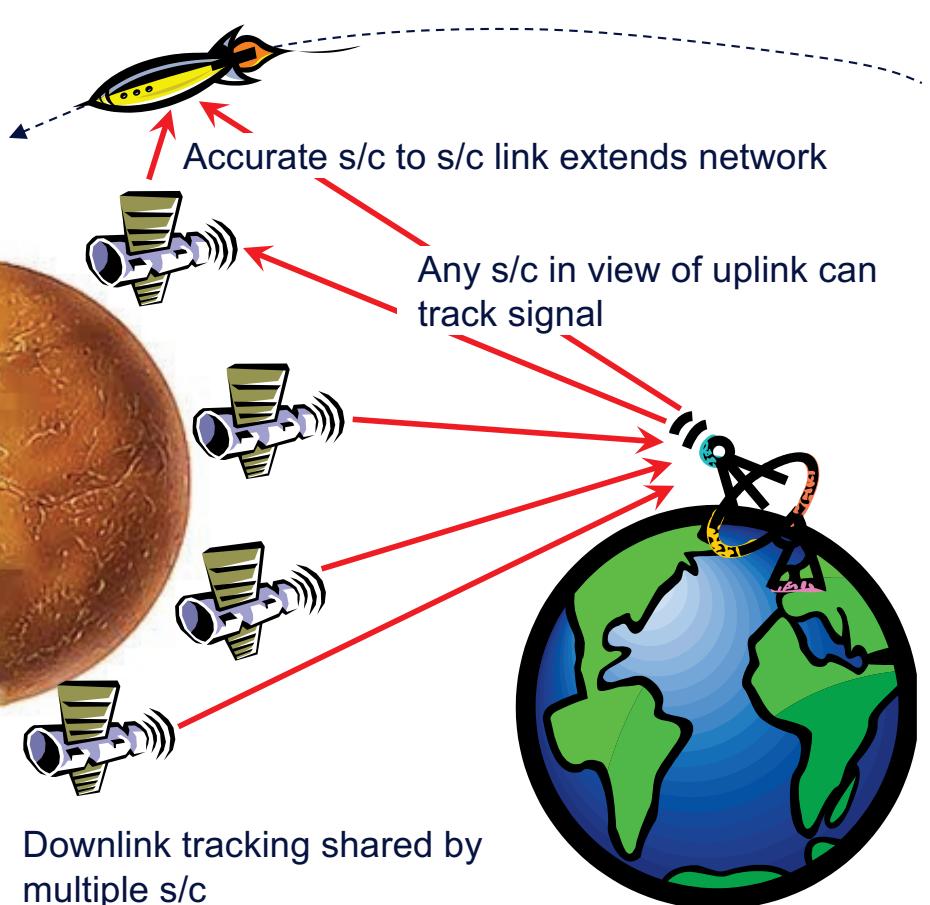
- One-way tracking improves existing tracking and onboard timing capabilities
 - Increase tracking data quantity via efficient use of uplink or downlink signals
 - Utilize multiple spacecraft per aperture downlink tracking – 2-3x more tracking for Mars assets
 - Enable use of uplink tracking with low gain antennas on s/c
 - » 3x more radio science and navigation data during Europa flybys
 - » Continuous tracking of *all* Mars s/c carrying DSAC
 - Eliminate need for three-way tracking at distant locations – removes multiple Earth antenna geometry and availability constraints
 - Increase bandwidth for downlink communications – use uplink for ranging

DSAC Enables a Scalable DSN Tracking Architecture

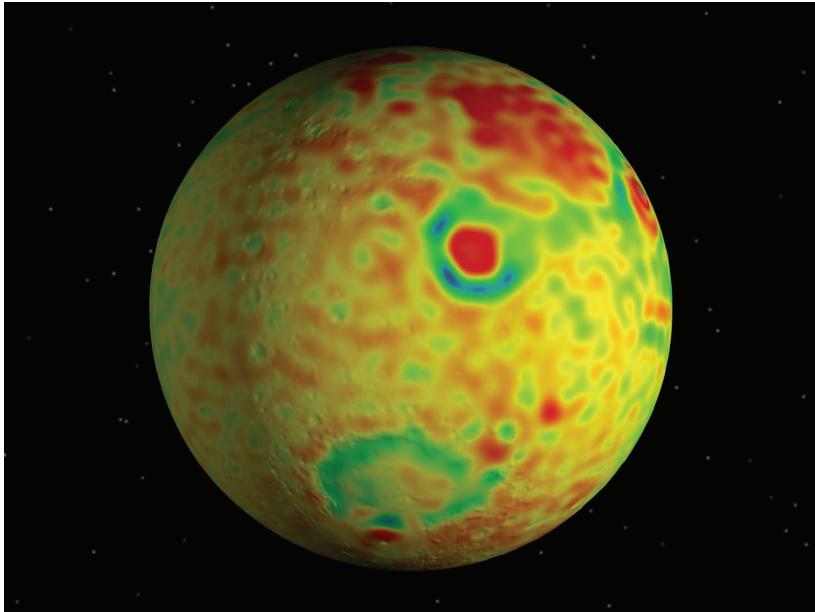
Today's 2-Way Navigation



Tomorrow's 1-Way Navigation w/ DSAC Onboard
One antenna supports multiple s/c simultaneously



DSAC Enhances Science and Enables Robust Onboard Navigation

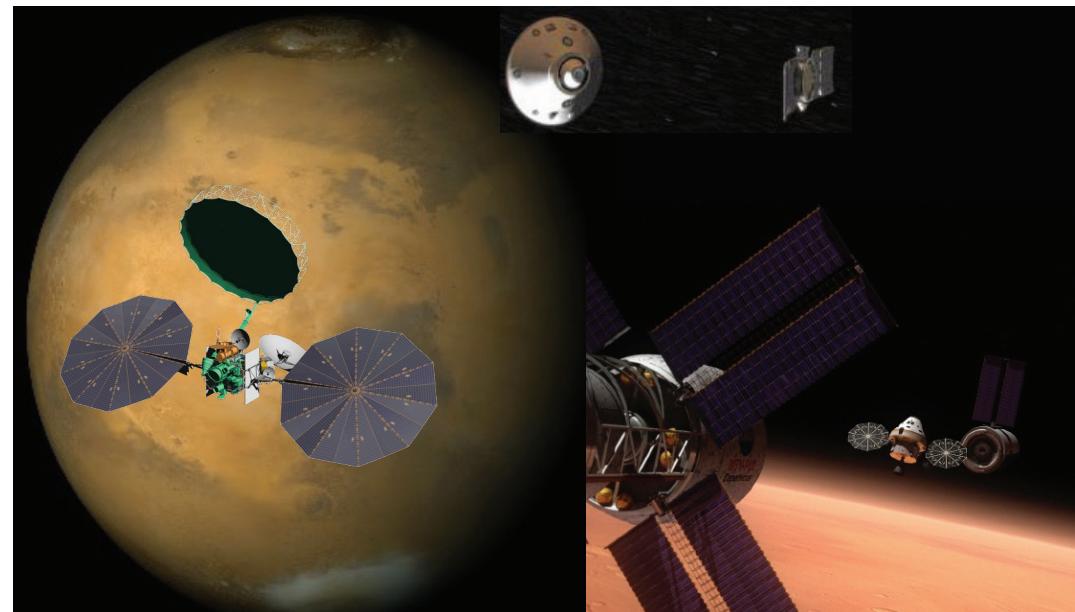


Real time, onboard deep space radio navigation system with DSAC yields

- Trajectory knowledge to 10s of meters at Mars atmosphere entry
- Enhanced navigation operations such as SEP spiraling into a low-altitude orbit
- Fault tolerant, robust navigation solutions required for safe human exploration

DSAC enables use of existing DSN Ka-band downlink tracking capability

- Ka-band data an order of magnitude more accurate than X-band data
- Determine Mars long-wavelength, time variable gravity effects to GRACE-quality with single s/c
- Improve ring/atmosphere measurements by 100 x

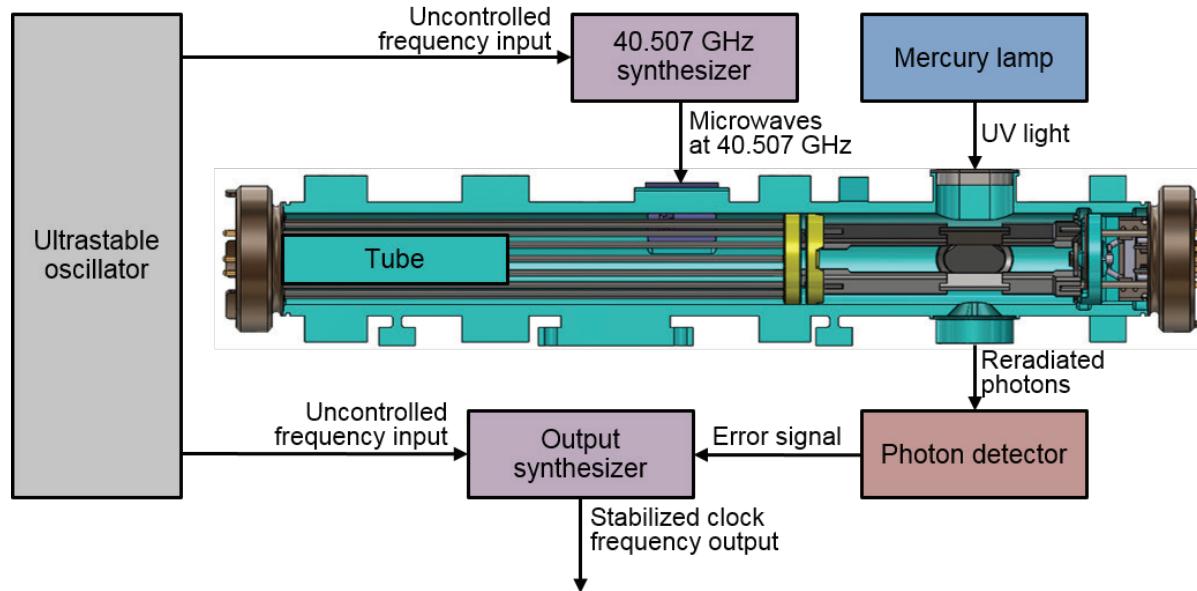


GPS and Other DOD Applications



- DSAC short and long term performance needed for future GPS uses (FAA & autonomy) – DSAC short term performance is 10X better than RAFS, and long term performance 50X better
- DSAC performance sufficient for future GPS III URE goals (improved clocks needed to shorten a ‘tent pole’ contributing to URE – ephemeris error is the other ‘tentpole’)
- DSAC performance (considering no intrinsic drift) well suited for autonomous operations needed for secure command and control satellite systems (follow-on AEHF) and other government agencies

Technology & Operation



Ion Clock Operation

- Short term (1 – 10 sec) stability depends on the Local Oscillator (DSAC selected USO 2e-13 at 1 second)
- Longer term stability (> 10 sec) determined by the “atomic resonator” (Ion Trap & Light System)

Key Features for Reliable, Long-Life Use in Space

- No lasers, cryogenics, microwave cavity, light shift, consumables
- Low sensitivity to changing temperatures, magnetics, voltages
- Radiation tolerant at levels similar to GPS Rb Clocks

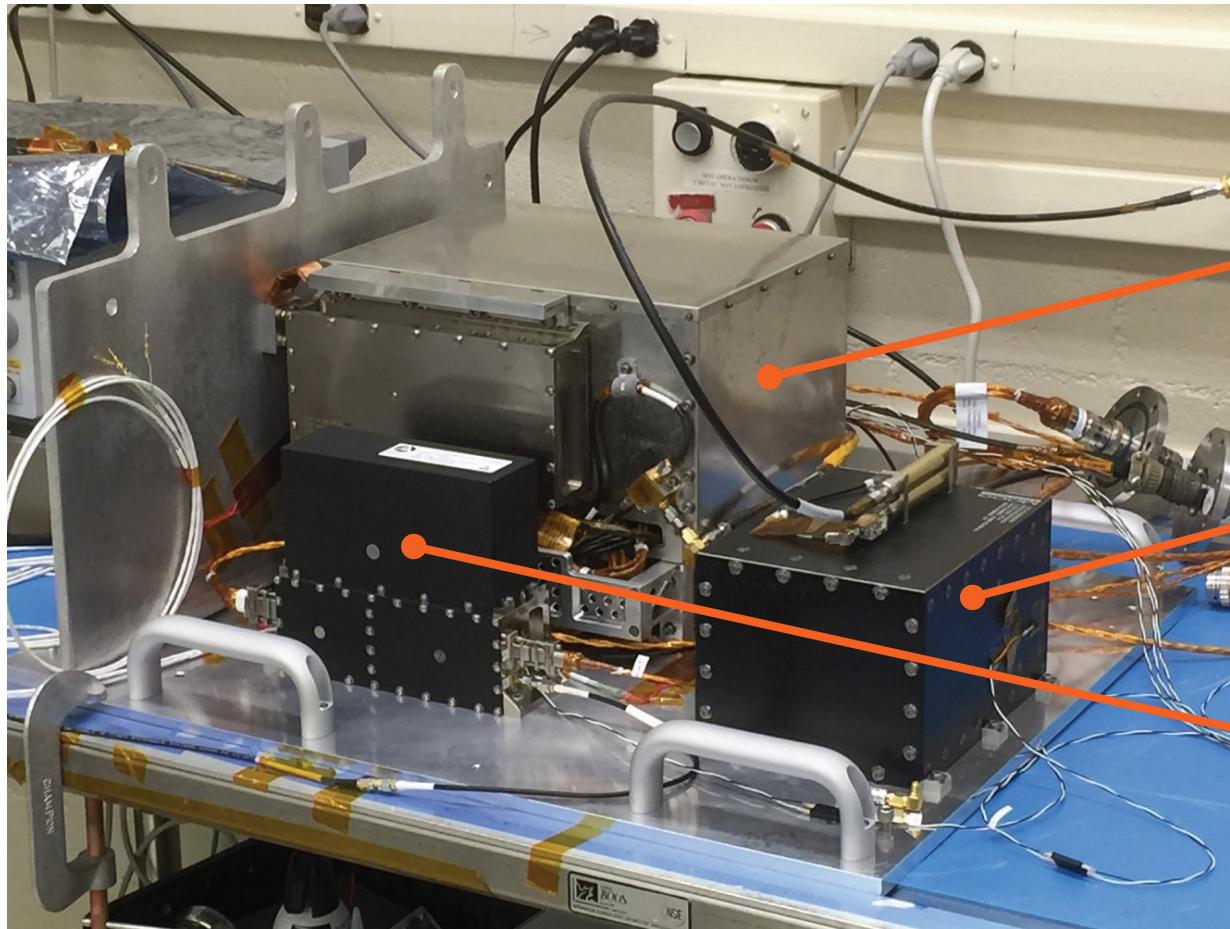
Ion Clock Technology Highlights

- State selection of $10^6\text{-}10^7$ $^{199}\text{Hg}^+$ electric-field contained (no wall collisions) ions via optical pumping from $^{202}\text{Hg}^+$
- High Q microwave line allows precision measurement of clock transition at 40,507,347,996.8 Hz using DSAC/USO system

$$SNR \times Q < \frac{5 \times 10^{-13}}{\sqrt{\tau}} \quad \& \quad A.D. < 3 \times 10^{-15}$$

- Ion shuttling from quadrupole (QP) to multipole (MP) trap to best isolate from disturbances - QP only implementation offers major simplification
- Ions are in an uncooled Neon buffer-gas

Payload Integration & Test on Flight Hardware



DSAC Demo Unit (DU)

Atomic Resonator (JPL)

V: 285 x 265 x 228 mm

M: 16 kg, Physics Pkg – 6.6 kg

P: 45 W, Physics Pkg – 17 W

GPS Receiver

Validation System (JPL-Moog)

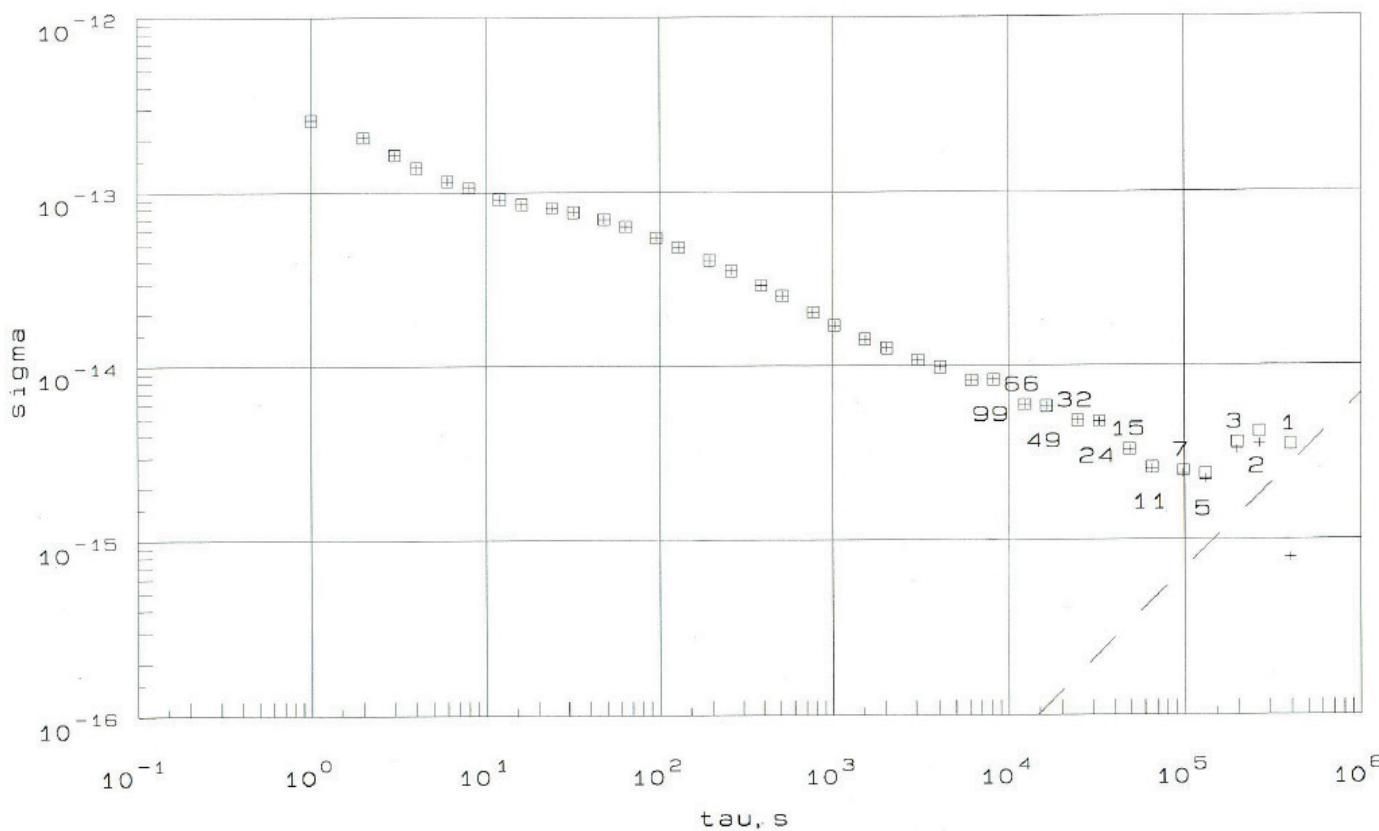
Ultra-Stable Oscillator (USO)

Local Oscillator (FEI)

Demo Unit designed for prototyping flexibility – room to optimize mass, power, and volume.

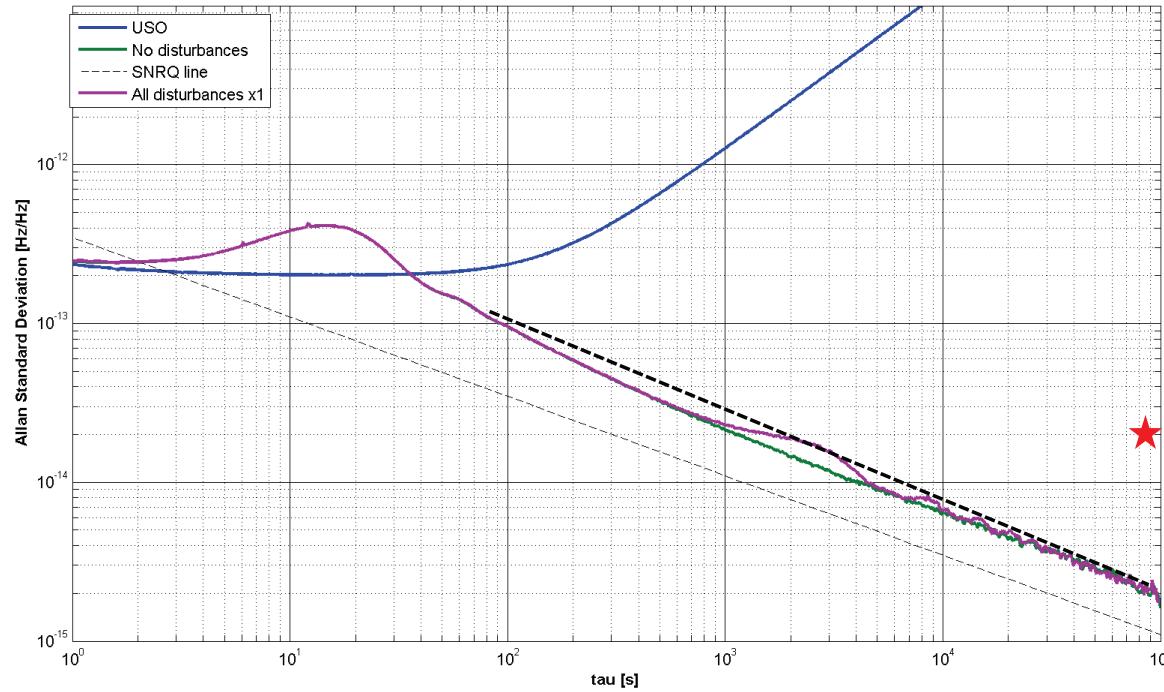
Demo Unit Measured Stability (Maser Input)

```
161219_1656 Chn 6 Osc.freq.: 2.046E+07 Hz Period: 1.0001217090+00 s
281/OSAC DU vs 281/HS9004A CH4 20.456001MHz
Span: 161219.165612 to 170103.070113, 1260301 s
Here: 161224.180000 to 170103.070000, 824400 s
        435828          1260228
Est.drift: -8.398E-16/d, Sigma: 1.177E-15 Gross □ Net +
```



- Results show DU with Maser input at constant temperature operating in QP-only mode
- DU/USO configuration tested with similar results (some transients present due to post-vibe testing effects)
- Stability $\sim 3e-15$ @ 1-day

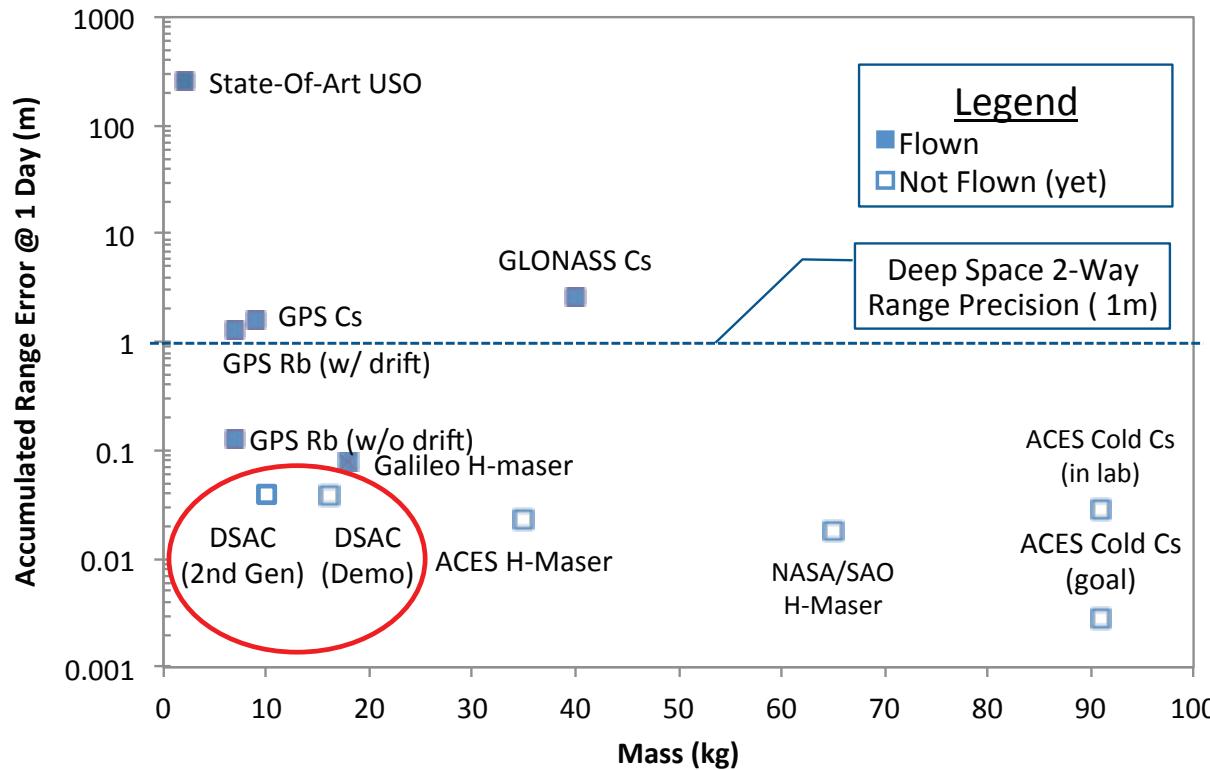
Model-based simulated on-orbit performance of DSAC in QP mode



- DSAC is predicted to have an AD $\sim 3\text{e-}15$ with expected orbital thermal and magnetic variations
- GPS systematic errors (predicted to be $\sim 2.2\text{e-}15$) raises this to $\sim 3.7\text{e-}15$ (via rss'ing)
- Using 14 days of data (nominal operational cadence), yields an equivalent 1-sigma upper confidence limit of $\sim 4.1\text{e-}15$

On-orbit performance expected to be verified at $< 5.\text{e-}15$ at one-day

DSAC Compared to Other Space Clocks

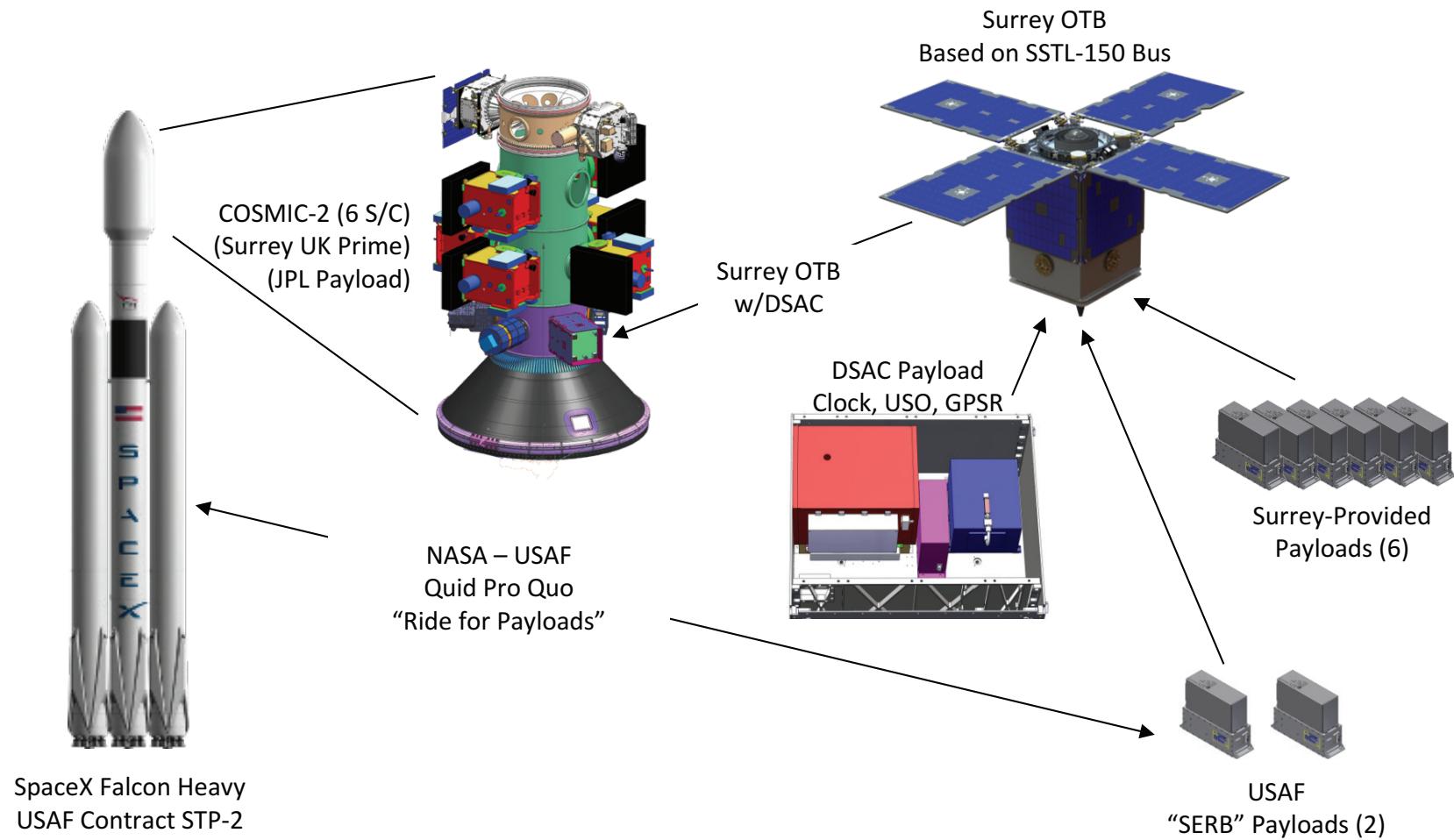


Atomic Frequency Standard	Mass	Average Power
DSAC Demo Unit (1 st Generation)	16 kg	< 50 W
DSAC Future Unit (2 nd Generation)	< 10 kg	< 30 W
GPS IIF Rb (5 th Generation)	7 kg	< 40 W
Galileo H-Maser (2 nd Generation)	18 kg	< 60 W

- Anticipated Allan Deviation (including drift) of $< 3\text{e-}15$ at one-day will outperform all existing space atomic frequency standards
- Mass and power of DSAC Demo Unit competitive with existing atomic frequency standards – future version could be < 10 kg and < 30 W with modest investment

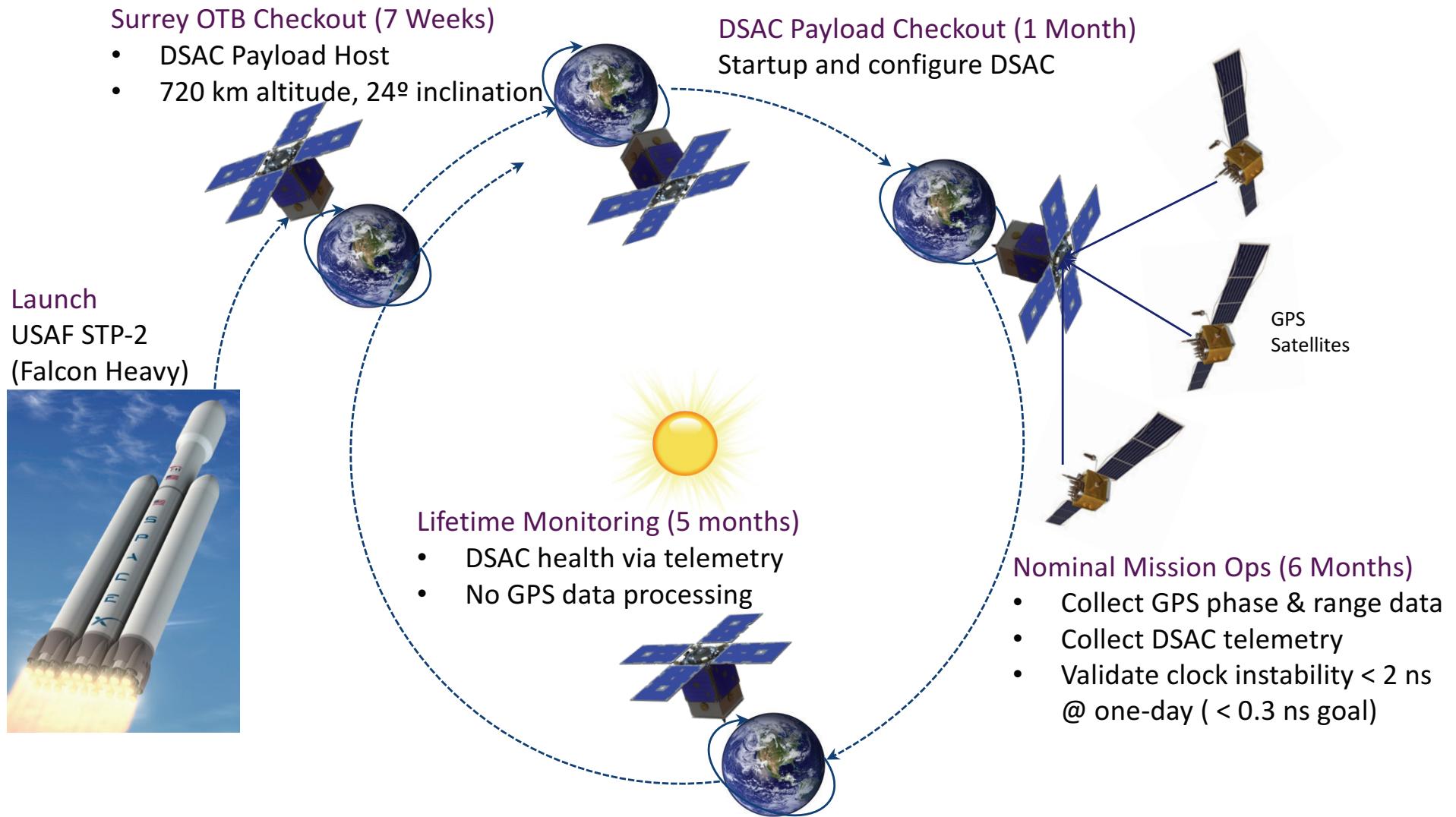
DSAC is an ideal technology for infusion into deep space exploration and national security systems

Ride Story



Flight Services Agreement in Place (S/C Host), STP-2 MOU Signed (LV), Ground Stations AF/JSC ...

Mission Architecture and Timeline



DSAC currently being integrated with OTB. Launch Sept 2017+ for one-year demonstration



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